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TRIALS TO DETERMINE THE CONSEQUENCES OF THE ACCIDENTAL IGNITION OF STACKS OF HAZARD DIVISION 1.2 AMMUNITION

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1. Introduction

To date nearly all international effort in the field of accidental explosion consequence determination has been aimed at the quantification of the effects of a Hazard Division (HD) 1.1, mass detonation, event in an explosives storage facility. Trials such as those carried out in Australia, France and the United States (US) over recent years have assessed the effects of blast and fragment throw from accidental mass explosions in brick and concrete storehouses, igloos and tunnel magazines.

Little attention has been paid to quantifying the consequences of the accidental ignition of HD 1.2 ammunition. This class of ammunition is not expected to explode en masse. Individual rounds will explode when sufficiently stimulated (by, for example, fire) without causing others around them to explode. Such explosions will continue spasmodically over a period as further individual rounds receive sufficient stimulus. Current HD 1.2 quantity–distance (Q-D) guidance within NATO and UK is "based upon US trials". Unfortunately literature searches have, to date, failed to unearth any record of these trials. US guidance does not follow that of NATO and UK and their methodology is based on a determined maximum fragment throw distance for the munition under consideration. More detailed descriptions of the NATO, UK, and US methodologies are given below.

In 1989 NATO AC 258 (Group of Experts on the Safety Aspects of Transportation and Storage of Military Ammunition and Explosives), acknowledging the frailty of the basis for their HD 1.2 Q–D's, agreed that a program of trials should be carried out to investigate the consequences of an accidental HD 1.2 event with the aim of revising the current NATO quantity-distance relationships and placing them on a firmer footing. Exposed stack trials and trials within typical storehouse structures were proposed. This program would also offer the opportunity for the development of an approach common to and acceptable to NATO, UK and US for the calculation of HD 1.2 safety distances.

To enable the program of trials to proceed in a short timescale, the UK Explosives Storage and Transport Committee (ESTC) and US Department of Defense Explosives Safety Board (DDESB) agreed to finance jointly an initial series of trials to examine the consequences of the accidental ignition of stacks of HD 1.2 ammunition in the open. This paper describes the current rules and underlying philosophies governing the storage of HD 1.2 ammunition in the US, UK and NATO. It then describes in detail the trials program, methodology and results obtained so far

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and makes some initial suggestions for the revision of the quantity-distance relationships for HD 1.2 storage. In conclusion the future program of trials is described.

2. US Hazard Division 1.2 Quantity–Distances

US explosives quantity–distance standards are defined in DOD 6055.9–STD, the Department of Defense Ammunition and Explosives Safety Standards. For HD 1.2 items, safety distances are related to the maximum range of hazardous projections as determined by specified Hazard Classification Tests. Four Inhabited Building Distances (IBD) (400, 800, 1200 and 1800 feet) are specified within which "most projections for given items will fall". However, very recently a revised methodology has been introduced in which IBD's based on hazardous fragment range test results may be defined in 100 foot increments with a 200 foot minimum[1]. This method has only recently been approved by the US joint hazard classifiers and DDESB. The test method for assigning items to the four categories (400, 800, 1200 and 1800 ft) given in the US DOD Explosives Hazard Classification Procedures is still a valid method[2].

The tests specified for definition of IBD in 100 ft increments for an item of ammunition are either a single or three "unconfined stack tests, bonfire tests or any combination thereof with 360 degree fragment recovery". To determine the IBD, if a single test is used, the maximum hazardous fragment throw distance is determined; it is rounded up to the next 100 ft and either 100 or 200 feet added dependent on the size of the item. If three tests are carried out, the maximum hazardous fragment throw distance is determined from all three trials and it is then rounded up to the next 100 feet. There is no additional increment added.

The remaining distances (public traffic route, intraline and above–ground magazine) are, with minor deviations, defined as percentages of IBD.

Public Traffic Route Distance takes account of the transient nature of the exposure and is calculated as 60% of IBD.

Intraline or Explosives Workshop Distance takes account of the extended period over which the event occurs and the consequent potential for evacuation. It is calculated as 50% of IBD. If the net explosive weight (NEW) at an operating line potential explosion site (PES) is limited to 5000 lb for items with IBD between 500 and 1200 ft then the Intraline Distance may be reduced to 200 ft.

Above–ground Magazine Distance "provides a high degree of protection against any propagation of explosion" excepting that "Items of this class/division with IBD requirements of 1200 ft or greater present a risk of propagation to adjacent above–ground magazines, particularly when packed in combustible containers. Storage in earth–covered magazines is therefore preferred". It is calculated as follows

For IBD less than 400 ft – 50% of IBD.

For IBD between 400 and 700 FT – 200 FT.

For IBD of 800 ft or greater – 300 ft.

The distances described above are independent of the NEW in the structure concerned. However, for items with IBD greater than 800 ft there is a storage limit of 500,000 lb NEW.

Recently a further "subset" of HD 1.2 has been defined – Unit Risk Class/Division 1.2. Ammunition. This type of ammunition is highly insensitive to accident stimuli and it is expected that only one round will react. IBD is calculated using the HD 1.1 areal number density criterion (one lethal fragment per 600 ft^2) for a single round of the ammunition.

3. <u>NATO and UK Hazard Division 1.2 Quantity Distances</u>

Current NATO and UK quantity–distance prescriptions are defined in Allied Ammunition Storage and Transport Publication 1 (AASTP–1) for NATO and ESTC Leaflet 5 Part 2 for UK. They differ in principle from those of the US in that they do not rely on the results of device-specific tests giving device–specific distances. There is a broad division, based loosely on calibre, into

(i) those items which give small fragments of moderate range (HD 1.2*).

(ii) those items which give large fragments with considerable range (HD 1.2).

The generally accepted divide is 60mm calibre though it is emphasized that this is not absolute. Where explosion effects trials data exists for the item or it is considered necessary to produce it, this may be used to support the allocation of the appropriate classification.

The prolonged nature of the event is considered in terms of fire fighting response, time for evacuation of exposed sites both within and external to the explosives area and time for closure of traffic routes. The protection afforded to ammunition and personnel at exposed sites is also taken into account. As has been stated earlier, quantity–distances are based on US data which, to date, has not been traced.

Quantity–distances for HD 1.2 and 1.2* ammunition are defined as follows:

Inhabited Building Distance is based on an acceptable risk from fragments and is defined

(i) For HD 1.2* as $D1=53Q^{0.18}$ (D1 in meters, Q is NEW in kilograms) with a minimum of 180m and maximum of 410m. If the exposed buildings are isolated and can be evacuated promptly a fixed distance of 180m is allowed. Schools, hospitals, etc., must be at the D1 distance.

(ii) For HD 1.2 as $D2=68Q^{0.18}$ with a minimum of 270m and maximum of 560m. Under similar circumstances to the above a fixed distance of 270m is allowed. Schools, hospitals, etc., must be at the D2 distance.

It is believed that the IBD Q–D formulae may relate to a lethal fragment density (fragment energy>80J) of one per 56m^2 though this is not certain.

Public Traffic Route Distance is based on "an acceptable risk from fragments and lobbed ammunition to be expected in the first half hour of an incident". It is defined such that if traffic can be stopped promptly, presumably within the half hour period, half the fixed IBD distances may be used. Failing this the full D1 and D2 distances are to be employed.

Intraline or Explosives Workshop Distance is a fixed distance of 25m for exposed sites with "virtually complete protection". Otherwise 90m or 135m are to be used for HD 1.2* or HD 1.2 ammunition respectively.

Inter–magazine distances are fixed distances of 2m, 10m, 25m or 90m dependent on the degree of protection provided at the exposed site.

4. Test Program

The trials described herein are bonfire tests on palletized 105mm cartridges stored in the open. This initial series will consist of at least seven tests, five of which have already been completed. Each of the first three tests was conducted using a single pallet of cartridges (single pallet tests). The fourth and fifth tests were conducted using eight pallets each (8-pallet tests). The sixth test will be conducted using 27 pallets. The primary intent in using at least three different stack sizes is to determine which, if any, parameters scale as a function of stack size. The type and quantity of ammunition to be used in any test beyond the sixth is still to be decided.

The single pallet tests and the 8-pallet tests were conducted during the period May 1991 through April 1992. The 27-pallet test should be completed in the fall of 1992. The test site for the initial series of tests is the Naval Air Warfare Center, China Lake, California.

5. Test Items

The M1 105mm cartridge is a semi-fixed, high explosive artillery round. The general configuration of the assembled cartridge is illustrated in Figure 1. Several variants of the M1 cartridge have been produced with projectiles loaded with TNT explosive or Composition B explosive. This series of tests is being conducted using cartridges containing approximately 4.5 lbs of TNT explosive each. The projectile body is fabricated from forged steel and weighs approximately 25.8 lbs. An aluminum shipping plug is assembled into the nose of the projectile in lieu of a fuze. The propelling charge is comprised of approximately 3 lbs of M1 propellant contained in a spiral wrap steel case. Each propelling charge case weighs approximately 4.7 lbs.

The cartridges are packaged in wooden boxes for transport and storage. Each box contains two cartridges that are packaged individually in fiberboard sleeves as shown in Figure 2. The cartridges are oriented such that the projectile of one cartridge is adjacent to the propelling charge of the other cartridge (i.e., nose-to-tail arrangement). A complete pallet consists of 15 boxes. The boxes are secured on the pallet using steel banding.

6. Test Method

The first four tests (i.e., all three single pallet tests and the first 8-pallet test) were conducted generally in accordance with the methodology prescribed by the UN Recommendations on the Transport of Dangerous Goods (the UN Orange Book)[3]. The test items were stacked on a test stand that provided approximately 30 in clearance between the bottom of the stack and ground level. The stacking arrangements for the tests are illustrated in Figure 3. Dried lumber placed beneath the test stand and around the pallet(s) was used as kindling to provide fuel during the initial stages of the test. Four shallow troughs containing a small amount of gasoline were placed around

the base of the stack to provide an ignition source for the fire. The gasoline in the troughs was ignited using an electric squib. In order to eliminate ground cratering and burrowing of unexploded test items at the stack site (ground zero), the stack and bonfire were constructed over a steel deck that was supported by a concrete pad. A typical completed test setup is shown in Figure 4.

The fifth test (second 8-pallet test) was conducted in the same manner except that kindling was placed beneath the test stand only. This was done to simulate a more probable scenario in which the test item packaging and the energetic components are the primary fuel source for a fire. In the single pallet tests and the first 8-pallet test the amount of kindling lumber used was nominally the same (115 ft^3). Each pallet of ammunition contained approximately 8.2 ft^3 of lumber. Thus, of the total lumber in the stacks (the wood of the ammunition boxes plus kindling), the ammunition box contribution was only 6.6% in the single pallet tests and 36% in the first 8-pallet test. In the second 8-pallet test the ammunition box contribution rose to 57%. Figure 5 is a photograph of the completed setup for the second 8-pallet test.

The debris recovery area, a flat, dried lake bed, encompasses a full 360° azimuthally about ground zero. It has been scraped clear of virtually all vegetation to a range of 1300 ft. In order to facilitate recovery of the test item debris, this cleared region has been marked with a 10° x 200 ft grid as illustrated in Figure 6. Recovery of the test item debris is accomplished manually through systematic visual searches of the area by test personnel. The debris that are recovered inside the 200-ft range are not retained for analyses due to their large numbers. These debris are segregated according to type (i.e., projectile case piece, cartridge case piece, or miscellaneous) and the total weight of all pieces of each type is determined. The pieces of debris that are recovered between the 200-ft and 1300-ft ranges are identified according to the grid sector in which they are found. The pieces of debris that are recovered beyond 1300 ft are identified individually by the appropriate azimuthal zone and range. The post-test searches conducted to date have been limited to a range of approximately 2000-ft. Recovery beyond this range was not considered cost effective because the numbers of fragments landing beyond 2000-ft were thought to be too small to justify the time and manpower required to search such a vast area. Additionally, the likelihood of finding any of the few fragments that might lie in this region was considered low due to the presence of vegetation.

The test events are recorded using closed circuit video systems. Typically one or two video cameras are positioned approximately 500 ft from the test stack to record the events that occur within the immediate confines of the fire. Another two or three video cameras are positioned on hillsides overlooking the test area to record the general location of larger debris as it impacts the ground. The video signals are recorded on standard 1/2 in VHS videocassette tapes.

An attempt was made during each of the first four tests to determine the terminal flight characteristics (e.g., velocity, angle of fall, etc.) of fragments impacting within a selected sector by capturing their terminal stages of flight on video. However, a fragment impacted within the selected sector in only one test and in that instance the image size of the fragment was below the resolution of the video record.

Blast overpressures are measured to provide a means of analyzing each explosion (in particular, "simultaneous" multiple explosions) and to provide a time record of the whole event. Eight piezoelectric pressure transducers are located along the 0° and 90° radials at ranges of 50, 70, 100, and 200 ft. The elevation of each transducer is approximately 20 in above ground level. The response of each pressure transducer is recorded using analog FM tape recorders providing 20 kHz frequency response. Due to constraints on the instrumentation cable lengths that can be used with this type of transducer, the recorders and ancillary signal conditioning equipment are housed in a

shelter that is located approximately 500 ft from the test site. Because personnel cannot be adequately protected at this range, the recording equipment is controlled and monitored from a remote site located approximately 4000 ft from the recording equipment. The recording systems are controlled by a master remote control station that sends commands and receives status reports through Dual Tone Multi-Frequency (DTMF) encoded radio transmissions. Each recorder, when operated at the required frequency response, provides approximately 50 minutes of usable recording time. Extended continuous recording for these relatively prolonged tests is obtained by operating multiple recorders sequentially so that their recording times overlap slightly.

7. Results

In general each of the tests produced events that were on the order of 1 hour duration. After ignition, the fire developed rapidly, enveloping the entire stack within three to five minutes. Typically the first reactions were observed about 15 to 20 minutes after ignition of the fire. These initial reactions were seen as localized areas of intense burning and were occasionally accompanied by a small flash and/or a low level audible report (pop). It is believed that these initial reactions were mild deflagrations of propelling charges and subsequent burning of the spilled propellant. Significantly more violent reactions, believed to be explosions of projectiles, would begin to occur several minutes later. These reactions were characterized by abrupt instantaneous expansion of the fire, a loud audible report, and localized scattering of burning wood and other debris about the test site. Additionally, large pieces of test item debris could often be seen impacting in the recovery area following one of the larger reactions (explosions).

Typically the fire would continue to burn at full intensity only until the first few explosions had occurred. It would then begin to die out slowly due to scattering of the stack by each successive explosion. Both the smaller, burning type reactions and the explosions continued to occur intermittently throughout the duration of the fire. Additionally, in each test, several explosions were observed after the fire was reduced to broadly scattered pieces of smoldering debris. It has appeared in all instances that the explosion reactions have occurred in the immediate vicinity (i.e., within 50 ft) of the fire. Neither on-site observations nor video records from the tests have provided any indications of test items being thrown significant distances prior to reacting. However, in each test some unreacted projectiles have been recovered several hundred feet from ground zero. The following sections summarize briefly specific observations for each of the tests. The event times are given in the form "minutes:seconds", e.g. 20:35.

Single Pallet Test No. 1. The first indications of test item reactions were observed 15:32 after ignition of the fire. The first major reaction, believed to be a projectile explosion, occurred 18:24 after ignition of the fire. The fire was reduced to broadly scattered smoldering debris after approximately 25 minutes. A total of 13 explosions were observed during and after the fire. Following the test, 17 projectile bodies were recovered intact. A total of 78 pieces of debris were recovered beyond the 200 ft range including 44 projectile case (and rotating band) pieces with a total mass of 139.5 lb_m and 19 cartridge case pieces with a total mass of 5.1 lb_m. The projectile case pieces and cartridge case pieces that were recovered inside the 200-ft range had total masses of 118.5 lb_m and 130 lb_m, respectively. The total mass of all recovered projectile case pieces accounts for approximately 77% of the estimated mass of the projectile bodies that were not recovered intact (i.e., estimated percentage of recovery based on mass). Similarly, the total mass of all recovered cartridge case pieces accounts for approximately 96% of the mass of the cartridge cases that were in the pallet.

Single Pallet Test No. 2. The first indications of mild deflagration reactions and burning reactions were observed 20:22 after ignition of the fire. The first explosion occurred 24:14 after ignition of the fire. The fire was reduced to broadly scattered smoldering debris after approximately 35 minutes. A total of 9 explosions were observed during and after the fire. Following the test, 21 projectile bodies were recovered intact. A total of 37 pieces of debris were recovered beyond the 200 ft range including 31 projectile case pieces with a total mass of 153.5 lb_m and one cartridge case piece with a mass of 2.5 lb_m. The projectile case pieces and cartridge case pieces that were recovered inside the 200-ft range had total masses of 66.0 lb_m and 136.3 lb_m, respectively. The corresponding estimated percentages of recovery based on mass are 95% for projectile case pieces and 99% for cartridge case pieces.

Single Pallet Test No. 3. The first indications of test item reactions were observed 20:05 after ignition of the fire. However, the first explosion was not observed until 36:48 after ignition of the fire. The fire was reduced to broadly scattered smoldering debris after approximately 60 minutes. A total of 11 explosions were observed during and shortly after the fire. Following the test, 18 projectile bodies were recovered intact. Additionally, a 19th projectile body was recovered nearly intact (moderate splintering in nose region). A total of 49 pieces of debris were recovered beyond the 200 ft range including 42 projectile case pieces with a total mass of 140.5 lb_m and three cartridge case pieces with a total mass of 4.1 lb_m. The projectile case pieces and cartridge case pieces that were recovered inside the 200-ft range had total masses of 85.6 lb_m and 134.5 lb_m, respectively. The corresponding estimated percentages of recovery based on mass are 73% for projectile case pieces and 98% for cartridge case pieces.

8-Pallet Test No. 1. The first indications of test item reactions were observed 18:13 after ignition of the fire. The first explosion occurred 20:48 after ignition of the fire. A total of 66 explosions were observed during and shortly after the fire. Following the test, 174 projectile bodies were recovered intact. A total of 808 pieces of debris were recovered beyond the 200 ft range including 263 projectile case pieces with a total mass of 593.4 lb_m and 320 cartridge case pieces with a total mass of 88.4 lb_m. The projectile case pieces and cartridge case pieces that were recovered inside the 200-ft range had total masses of 754 lb_m and 874 lb_m, respectively. The corresponding estimated percentages of recovery based on mass are 79% for projectile case pieces and 85% for cartridge case pieces.

8-Pallet Test No. 2. The first indications of test item reactions were observed approximately 14:15 after ignition of the fire. The first explosion occurred approximately 18:37 after ignition of the fire. A total of 65 major reactions were observed during and shortly after the fire. Following the test, 174 projectile bodies were recovered intact. Fragment recovery data for this test are not yet available.

The event times for the explosions that were observed during the single pallet tests are provided in Table 1. The event times for the explosions that were observed during the 8-pallet tests are provided in Table 2. The azimuthal and radial distributions of fragments recovered outside the 200-ft range (far-field fragments) after the single pallet tests and the first 8-pallet test are illustrated in Figures 7 through 10. Photographs of typical fragments are provided in Figures 11 and 12.

Table 1. Elapsed Times Until Explosions During Single Pallet Tests

	Elapsed Time (min:sec)		
Explosion No.	Test No. 1	Test No. 2	Test No. 3
1	18: 24	24: 14	36: 48
2	18: 51	27: 01	47: 05
3	19: 58	30: 57	49: 02
4	20: 43	33: 25	51: 10
5	20: 55	33: 33	54: 50
6	27: 40	38: 24	56: 29
7	27: 44	39: 09	57: 09
8	28: 50	41: 03	61: 29
9	29: 34	42: 36	63: 13
10	29: 51		67: 35
11	33: 48		78: 40
12	35: 21		
13	48: 53		

Table 2. Elapsed Times Until Explosions During 8-Pallet Tests

Test No. 1						Test No. 2					
No.	Time	No.	Time	No.	Time	No.	Time	No.	Time	No.	Time
1	20:48	26	33:49	51	41:18	1	18:37	26	25:04	51	29: 49
2	23:47	27	34:07	52	42:00	2	18:56	27	25:09	52	29: 50
3	23:57	28	34:10	53	42:16	3	18:53	28	25:15	53	29: 55
4	25:51	29	34:12	54	42:19	4	21:18	29	25:18	54	30: 30
5	26:32	30	34:44	55	42:23	5	21:25	30	25:28	55	30: 45
6	26:37	31	34:49	56	42:50	6	21:35	31	25:38	56	30: 58
7	27:13	32	35:04	57	43:13	7	21:43	32	25:41	57	31: 04
8	27:36	33	35:27	58	43:44	8	21:51	33	25:45	58	31: 33
9	27:44	34	35:28	59	44:13	9	21:53	34	25:50	59	32: 29
10	27:58	35	35:47	60	44:39	10	22:07	35	25:51	60	33: 43
11	28:22	36	36:11	61	46:25	11	22:12	36	25:55	61	36: 48
12	28:29	37	36:30	62	47:05	12	22:17	37	26:06	62	37: 28
13	29:23	38	36:42	63	47:46	13	22:57	38	26:16	63	38: 46
14	29:23	39	37:05	64	51:41	14	23:11	39	26:26	64	39: 28
15	29:58	40	37:15	65	52:58	15	23:34	40	26:30	65	41: 42
16	30:59	41	37:47	66	61:08	16	23:37	41	26:33		
17	31:04	42	38:38			17	23:40	42	26:41		
18	31:16	43	40:01			18	23:42	43	27:05		
19	31:22	44	40:07			19	23:56	44	27:09		
20	31:48	45	40:15			20	24:07	45	27:29		
21	31:54	46	40:22			21	24:09	46	27:44		
22	32:17	47	40:24			22	24:40	47	27:54		
23	32:24	48	40:24			23	24:44	48	28:34		
24	33:12	49	40:29			24	24:54	49	29:12		
25	33:16	50	41:18			25	24:55	50	29:13		

The blast data from these tests are too voluminous for inclusion in this paper. To date the blast data from each test have been used primarily to confirm, based merely on the presence of air shock, the number of explosions that occurred. However, analyses of the blast data are continuing in an attempt to estimate the locations of the test items when they reacted and to determine their yield.

8. Analyses

The recovery data for these tests have not been subjected to rigorous statistical tests. However inspection of Figures 7 through 10 suggests that the distribution of far-field fragments with respect to azimuthal angle about the stack is fairly random. Therefore, the following analyses are oriented primarily towards description of fragment hazards in terms of range, independent of azimuthal angle.

The recovery data were used to calculate areal densities of lethal fragments analogous to those used to establish hazard ranges for HD 1.1 items. In the absence of any means of determining fragment energies, all recovered fragments were assumed to be lethal, including some of the cartridge case pieces and miscellaneous debris recovered within the 200-ft to 400-ft range interval which had masses as low as 0.01 lb_m. Additionally, it was assumed that the distribution of fragments with respect to azimuthal angle is indeed random. Thus the areal density for each range interval was calculated as the total fragment count for the range interval divided by the area of the corresponding annulus. Pseudo trajectory-normal methods were used to determine the fragment count for each range interval inside the 1200-ft range[4]. For example, the fragment count for the 200-ft to 400-ft range interval was the number of fragments recovered between 200-ft and 1200-ft, for the 400-ft to 600-ft range interval it was the number of fragments recovered between 400-ft and 1200-ft, etc. The areal density for each range interval beyond 1200-ft was calculated based solely on the number of fragments recovered in that interval. The underlying assumption for this approach is that each fragment recovered inside the 1200-ft range followed a relatively low, flat trajectory and thus would pose a hazard to personnel and small structures located at ground level along its entire flight path. Conversely, each fragment landing beyond 1200-ft is assumed to have followed a relatively high trajectory with an extremely steep angle of fall in its terminal phase of flight. Under these circumstances, the fragment would not pose a hazard to personnel or small structures located at ground level except in the immediate vicinity of the point of ground impact.

The fragment densities determined in the preceding manner are shown graphically in Figure 13. In this figure the value of fragment density for each range interval is plotted at the midpoint of the interval. Additionally, densities are expressed in units of fragments per 600 square feet so that the results may be compared easily with the current HD 1.1 areal number density criterion. It can be seen immediately upon inspection of Figure 13 that the fragment densities for each of the single pallet tests were well below this criterion for all ranges beyond 200 ft. It can also be seen that the fragment densities for the first 8-pallet test were below the HD 1.1 areal number density criterion for all range intervals beyond 400 ft.

The fragment densities depicted in Figure 13 are based on the numbers of fragments actually recovered following each test. However, as indicated previously, these recoveries were incomplete. This is particularly true for projectile case fragments, which are the only type of debris thrown more than a few hundred feet. Thus the densities depicted in Figure 13 are probably optimistic; that is, they probably tend to understate the actual fragment hazard at most ranges, especially the further ranges. In order to derive more conservative estimates of fragment densities, the fragment recovery data were adjusted as follows to compensate for the apparent shortfalls.

a. The total mass of all far-field projectile fragments (m_f) was estimated as

$$m_f = Nm_p - m_0$$

where: N is the number of projectile bodies not recovered intact
m_p is the mass of each projectile body (25.8 lb)
m_0 is the total mass of all projectile pieces recovered inside 200-ft

b. The number of far-field projectile case fragments that were not recovered after each test ("missing" fragments) was estimated as

$$n_m = n_r[(m_f/m_r)-1]$$

where: n_m is the number of "missing" far-field projectile fragments
n_r is the number of far-field projectile fragments recovered
m_f is the estimated mass of all far-field projectile fragments
m_r is the total mass of all recovered far-field projectile fragments

c. The "missing" fragments were assumed to be located between the ranges of 1200-ft and 2600-ft. It is thought that this is the region where fragments are most likely to have landed but not been recovered for several reasons:

(1) The presence of vegetation may have shielded some fragments from the view of test personnel during post-test searches.
(2) Most of the fragments falling in this region would probably impact the ground at a relatively steep angle of fall thereby increasing the likelihood that they would penetrate the surface and remain buried.
(3) The region beyond the 2000-ft range was not searched thoroughly.

The specific distribution of the "missing" fragments was assumed to be such that an equal number were present in each 200-ft wide range interval between the 1200-ft and 2600-ft ranges. This assumption is considered conservative in that the fragment counts for the outer-most range intervals are probably much greater than would be expected for a more realistic scenario in which the number of fragments decreases with increasing range.

The preceding adjustment was applied for projectile case pieces only. The recovery data indicate that nearly all of the cartridge case pieces were recovered after each test and thus no further adjustment appears warranted.

The fragment densities obtained using the adjusted fragment counts are shown graphically in Figure 14. It can be seen that the fragment densities for each of the single pallet tests are still much less than one fragment per 600 ft^2 for all ranges beyond 200 ft and that the densities for the first 8-pallet test are still below this level for all range intervals beyond 400 ft. However, the indicated densities are considerably higher at the greater ranges than those obtained using the unadjusted fragment counts.

These same data are shown again in Figure 15 except that in this case the densities have been normalized on a per pallet basis. Inspection of this figure shows that the normalized fragment densities for the first 8-pallet test are roughly the same as those for the single pallet tests. This suggests that, at least for smaller stack sizes, fragment densities scale roughly linearly with respect

to the number of items in the stack. If it is assumed that fragment densities scale linearly as a function of the number of rounds for a broad range of stack sizes, then the results of the tests conducted thus far may be used to estimate the fragment densities that would be expected for events involving considerably larger stacks. The results of each of the single pallet tests and the first 8-pallet test were scaled up to obtain density-range estimates for various stack sizes up to 50000 rounds. The density-range estimates for each selected stack size were then fitted using a cubic spline fit to determine the range at which the fragment density would exceed one fragment per 600 ft^2. These estimated ranges are shown graphically in Figure 16. A comparison between these estimated ranges and the corresponding IBD's prescribed by current NATO/UK and US quantity-distance requirements for HD 1.2 items is provided in Figure 17.

All of the preceding description of fragment hazards has been based on final fragment densities resulting from the cumulative buildup of far-field fragments throughout each test. One of the distinguishing features of a HD 1.2 event relative to a HD 1.1 event is the prolonged period of time over which reactions occur. As can be seen in Tables 1 and 2, the time intervals over which explosions have been observed in the tests completed thus far range from approximately 19 minutes to approximately 42 minutes. The cumulative frequency distribution of the explosions that occurred in each test are shown in Figure 18 and Table 3 gives the times at which 20%, 50%, and 100% of the explosions have occurred for each test.

Table 3. Times After First Explosion at Which 20%, 50%, and 100% of Explosions Have Occurred

	Time in Minutes		
	$T_{20\%}$	$T_{50\%}$	$T_{100\%}$
Test 1	<5	10	31
Test 2	<5	9	19
Test 3	12	18	42
Test 4	9	14	41
Test 5	<5	8	24

9. Discussion

The current program of trials addresses the consequences of an accidental fire in exposed stacks of HD 1.2 ammunition. No work has yet been done to quantify the consequences of similar events inside structures (e.g., storehouses). Although the trials program is, as yet, incomplete, some patterns and trends are beginning to emerge from the results.

Times to first propellant reaction and to first explosion have all been in excess of 15 minutes and have not occurred until the stack is fully engulfed by fire with the wooden ammunition boxes contributing significantly to the fire. This is perhaps the worst case in the sense that the wooden ammunition cases formed a considerable proportion of the total fuel available (36% and 57% in the case of the two 8 pallet tests). The time to first event will vary with many factors (e.g., the amount of fuel available, packaging materials, calibre of rounds (thermal mass)), and the thermal sensitivity of the explosives used.

Following the first explosion the frequency of explosions builds up rapidly with time and then reduces at a lower rate towards the end of the event. Approximately one third of the rounds in the stack explode during the event.

No evidence of full detonation or of sympathetic reaction has yet been found. Pressure records indicate pressures less than those from a complete detonation and post–test examination of debris indicates that the aluminum closure plugs are forced out, presumably by expansion of the fill, and molten TNT then drains from the shell. Burning of the TNT has also been observed prior to explosions. Each round that explodes fragments the case in a "banana skin" fashion (Figures 11 and 12). Thus only a small number of heavy fragments per round are generated. If it is conjectured that HD 1.2 events in general will be low order explosions and cases fragment in similar fashion, the Q-D's may be related in part to number of rounds and not to NEW. A broad division by calibre similar to that used in the NATO definitions may then be used to define hazard distance bands (similar to those used in the US) as the range of fragment scatter will depend on the fragment dimensions and weights.

It is important to note that, although complete rounds are projected as far as 1100 ft from ground zero, there has been no occasion on which a round has exploded on or after impact other than those thrown a few feet and remaining within the zone of the fire. Thus, in calculating quantity distances, it will not be necessary to include any additional fragmentation effect attributed to far-field explosions.

As may be expected in an event in which the orientation of the rounds in the stack is destroyed after the first one or two explosions, there is no noticeable directional trend in the far-field fragmentation. The addition of the "missing" fragments into the overall fragment array assumes the same azimuthal randomness. The radial distribution of "missing" fragments (equal numbers per 200-ft annulus) implies a degree of conservatism as there is no decrease in numbers with range. There is of course a decrease in fragment density with range as the area of each annulus increases with its range. More realistic distribution of the "missing" fragments is still being investigated. The assumption that the trajectory normal analysis should only apply to fragments within 1200 ft of ground zero is based on the premise that, beyond that range, fragments must have been launched at high trajectory and thus would not contribute to lethality in the nearer field. Given the weight distribution of the far-field fragments all have been considered as lethal.

As Figure 15 shows, between the one and eight pallet tests, the fragment densities scale reasonably. Although the trials data gathered to date gives a good indicator of far-field fragment densities for small NEW's, extrapolation to larger quantities relies almost entirely on the "missing" fragments and the way they were introduced into the analysis. The estimated range to exceed one lethal fragment per 600 ft^2 asymptote (Figure 17) is an artifact of the "missing" fragment distribution used and illustrates

1. In the short term, the need to refine the distribution used for these "missing" fragments.

2. In the longer term, the need to examine the fragment pick-up philosophy and technique to reduce the number of "missing" fragments and get a realistic picture of the very far-field fragmentation.

Given a more realistic distribution, it is suggested that the curves should go asymptotic to the "No. of Rounds" axis at a range representing the maximum possible projection range for the fragments.

Figure 17 illustrates that, at small NEW's (where the gathered data applies), some savings over the existing criteria can be gained. However above 10000 rounds there is a sharp increase above the criteria. It must be re-emphasized that this is due to the conservatism built into the treatment of the "missing" fragments. As might be expected, all results fall below the IBD curve for HD 1.1.

Figure 18 and Table 3 clearly illustrate that there is considerable variation in the rate of explosions once they have started. It is therefore considered inadvisable to consider any period following the first explosion during which reduced lethal radii might be inferred. Thus any consideration of a time for evacuation should be limited to the minimum 15 minutes before the first explosion. The alarm must be raised when the fire starts. Thus automatic fire detection and alarm systems are an important requirement for optimum evacuation time availability. For similar reasons the use of automatic drench systems may be the only effective and safe means of fire fighting.

It is important to note that all the above discussion refers to the effects from exposed stacks of ammunition. Further reductions in the range of explosion effects will almost certainly be gained when the stacks are contained within storehouses.

10. Conclusions

A fire in an exposed stack of M1 105mm Cartridges will result in the progressive explosion of about one third of the projectiles over a period of one hour.

Full detonation of the rounds is not observed and the lower order explosions result in small quantities of large fragments. Due to their size, these are considered lethal over the whole projection range.

Fragments are dispersed randomly in azimuthal angle and the fragment density decreases rapidly with range from ground zero.

There is a minimum period of 15 minutes before any explosion occurs. After the first explosion the rate of explosions and consequent fragment projection increases unpredictably and rapidly. Time for fire fighting and evacuation may be limited to the initial 15 minutes.

Comparison of the results of these tests with existing Q–D definitions indicates that some lowering of Q–D's may be possible with small stacks (10,000 rounds) but further analysis of the existing data and development of the fragment recovery techniques is needed before reliable extrapolation to larger stack sizes can be made.

Further development of the post-trials fragment collection techniques must be made to improve the very far-field collection efficiency.

11. Future Work

At least two more firings are planned in the exposed stack program. A 27 pallet test is planned for October 1992 followed by a further 8 pallet test in 1993, possibly with a different calibre munition.

A program of tests to evaluate the consequences of accidental explosions in structures has been proposed. Current US and UK opinion is that the Q-D's predicted in this paper can be significantly reduced when surrounded by a reasonably strong building. Currently, efforts are aimed at determining the scope and depth of international interest in the program.

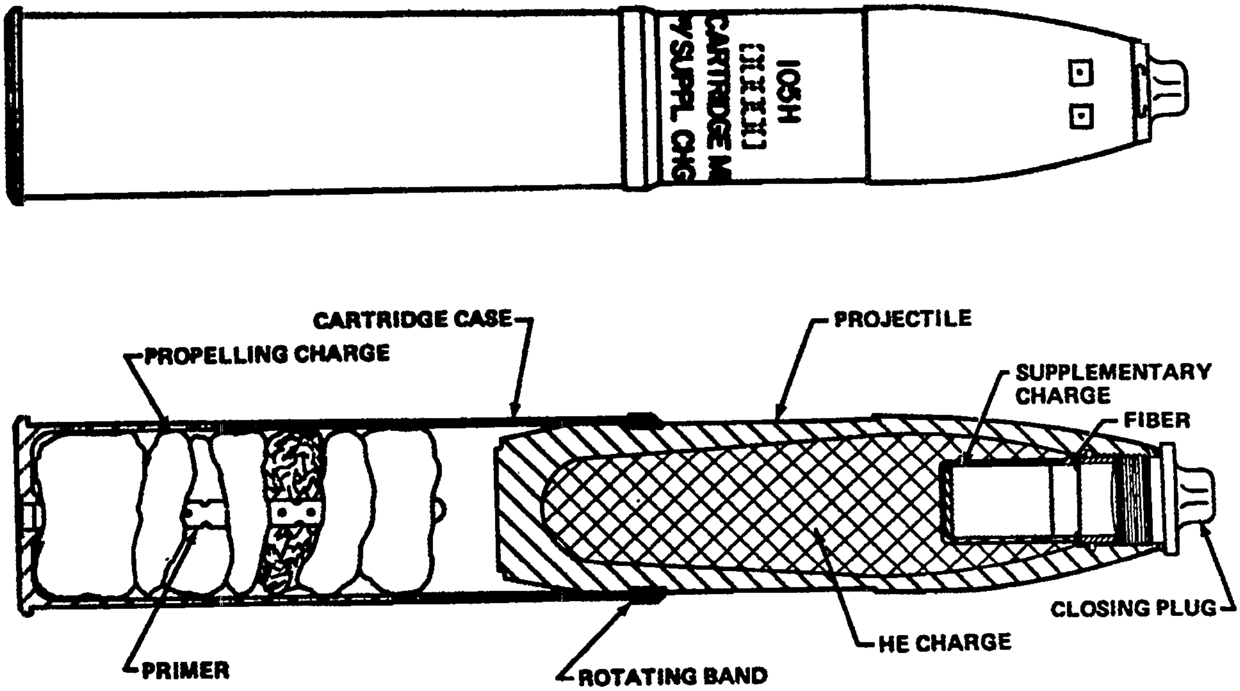
12. References

1. DDESB-KT memorandum dated 9 April 1991, Subj: New Class/Division 1.2 Hazard Classification Test Result Interpretations, Alternate Test Procedures, and New Quantity-Distance Considerations

2. Department of Defense Explosives Hazard Classification Procedures, NAVSEAINST 8020.8A (Army TB 700-2, Air Force TO 11A-1-47 Defense Logistics Agency DLAR 8220.1), December 1989.

3. United Nations Recommendations on the Transport of Dangerous Goods, ST/SG/AC.10/1 Current Revision

4. Swisdak, M.M., Jr., "Procedures for the Analysis of the Debris Produced by Explosion Events", Minutes of the Twenty-Fourth Explosives Safety Seminar, Adams Mark Hotel, St. Louis, MO, 28-30 August 1990, pp.2159 - 2175.



<u>Nominal Characteristics</u>

Projectile Body:	Forged Steel
Projectile Body Weight :	25.8 lb
Explosive Fill:	TNT
Explosive Weight:	4.5 lb
Propelling Charge Case:	Spiral Wrap Steel
Propelling Charge Case Weight:	4.7 lb
Propellant:	M1 propellant
Propellant Weight:	2.8 lb

Figure 1. M1 105mm Cartridge

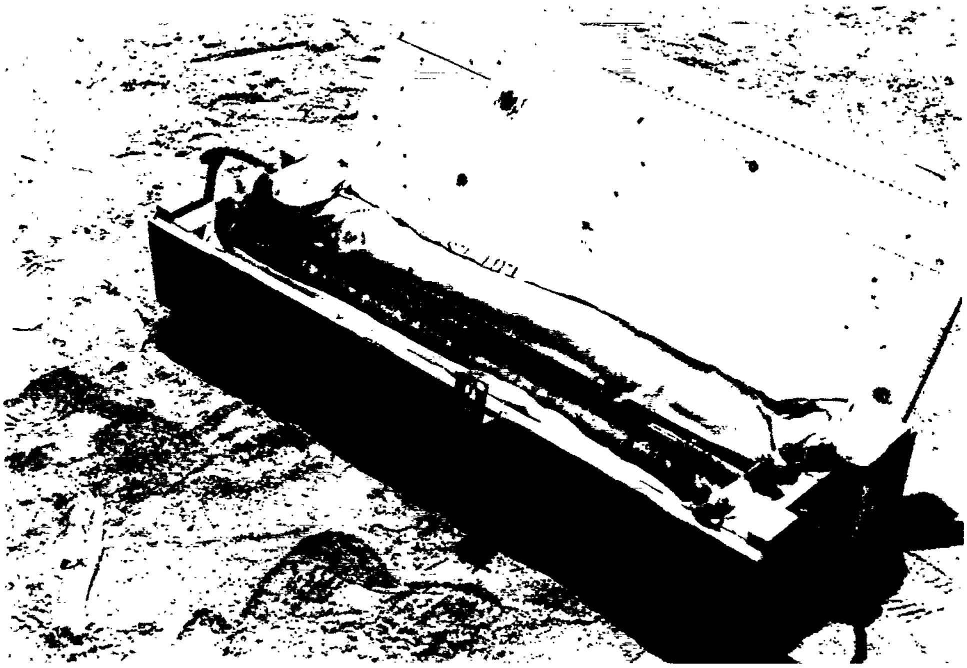
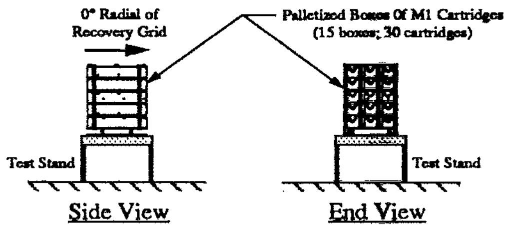
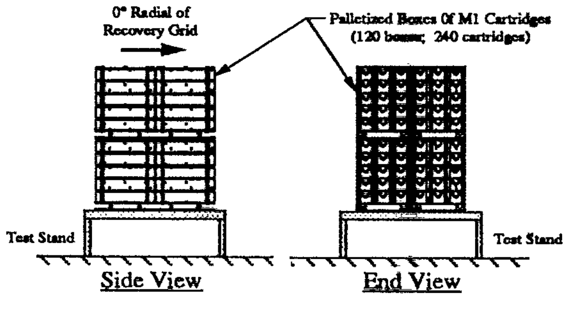


Figure 2. Packaging of M1 105mm Cartridges



Single Pallet Test



8-Pallet Test

Figure 3. Stacking Arrangement for Single Pallet and 8-Pallet Tests

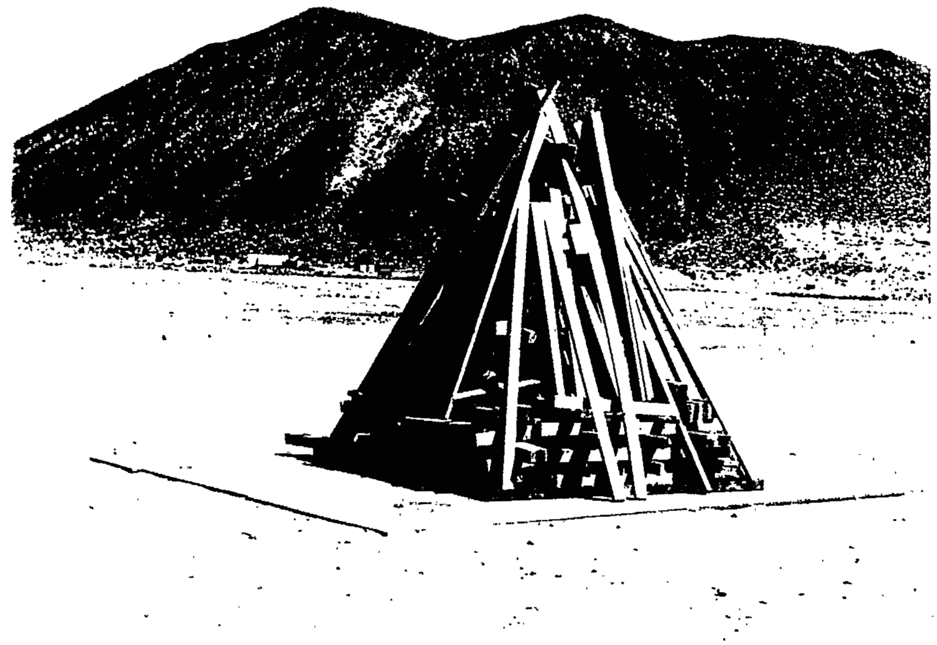


Figure 4. Typical Completed Test Setup for the Single Pallet Tests and the First 8-Pallet Test

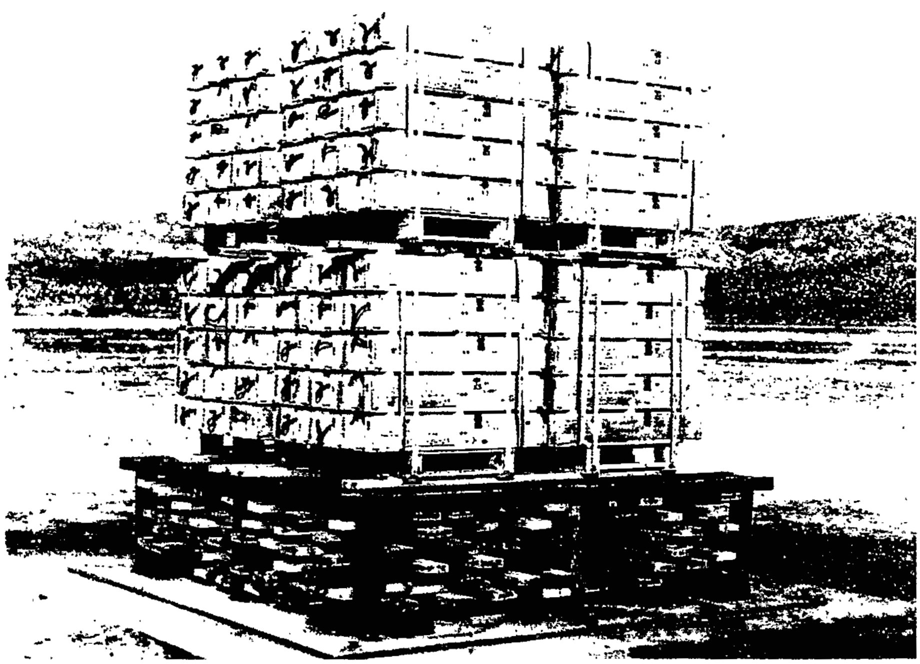


Figure 5. Completed Test Setup for Second 8-Pallet Test

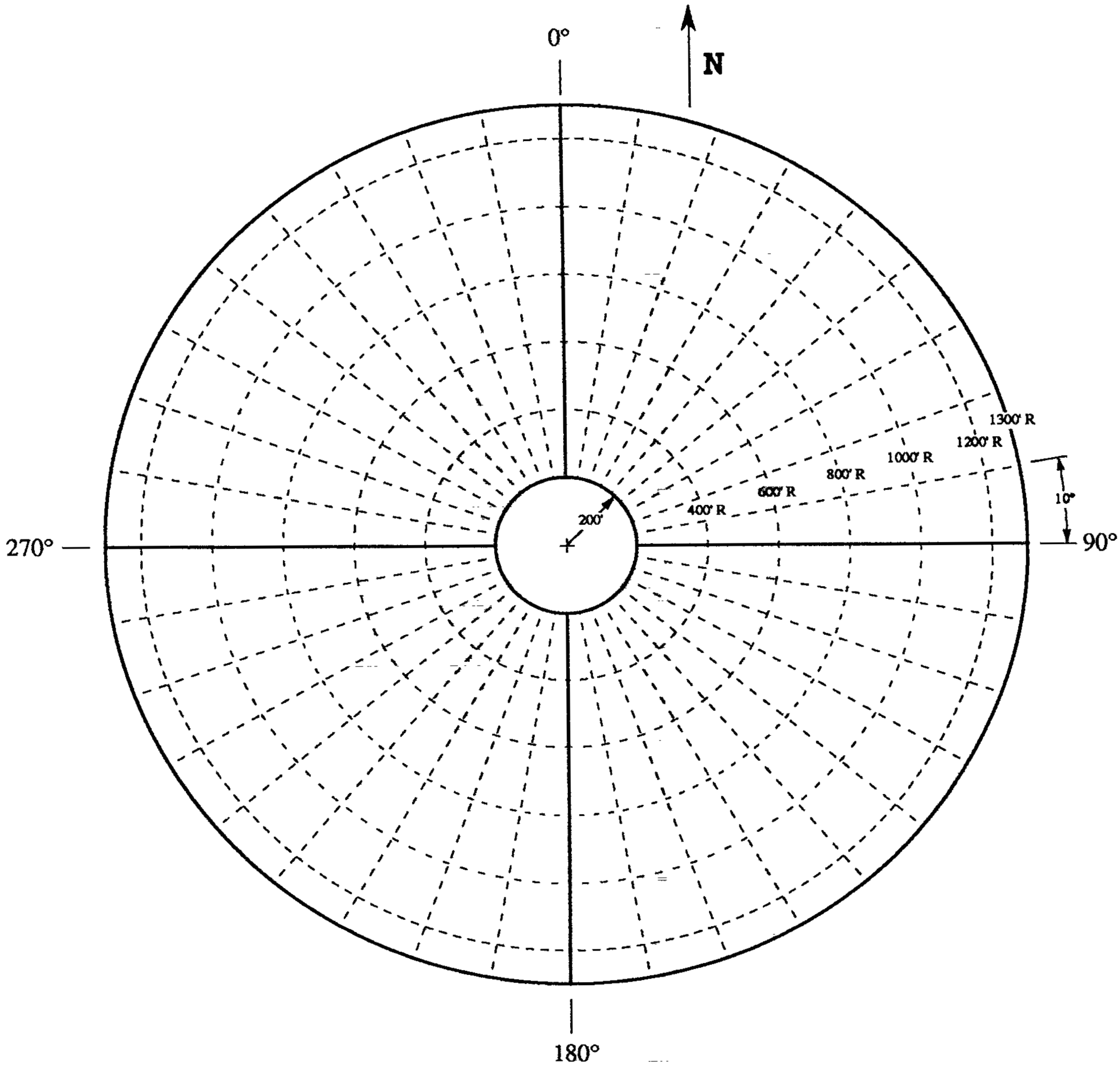


Figure 6. Recovery Grid for HD 1.2 Ammunition Hazards Tests

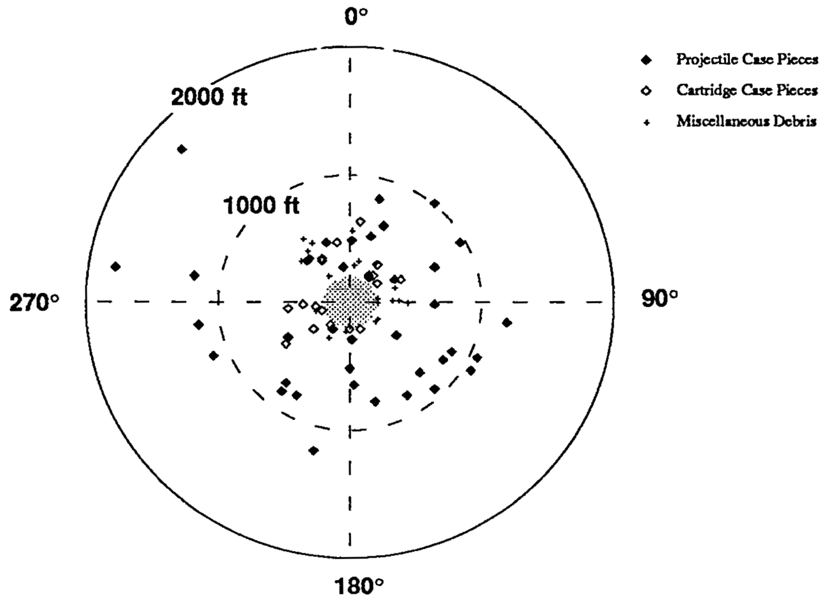


Figure 7. Approximate Distribution of Far-Field Fragments After First Single Pallet Test

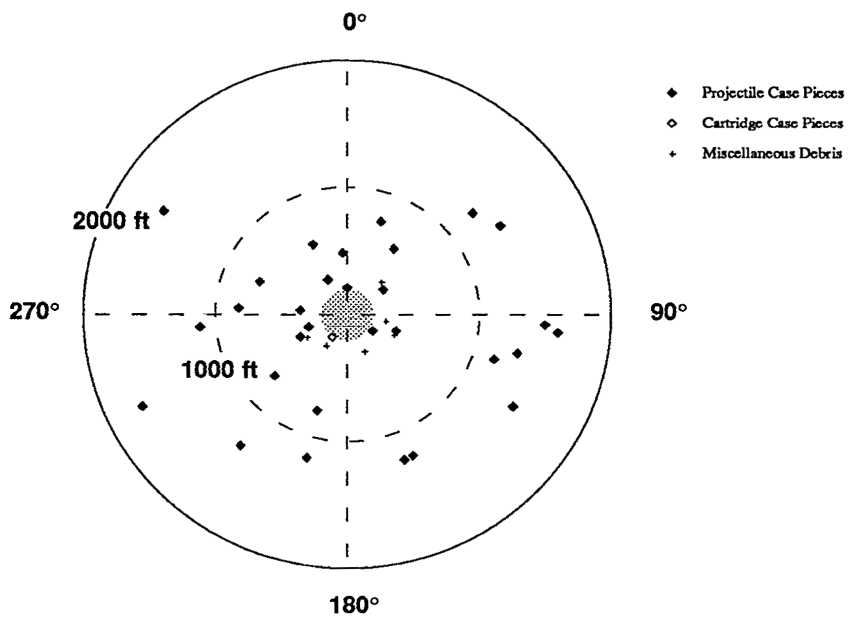


Figure 8. Approximate Distribution of Far-Field Fragments After Second Single Pallet Test

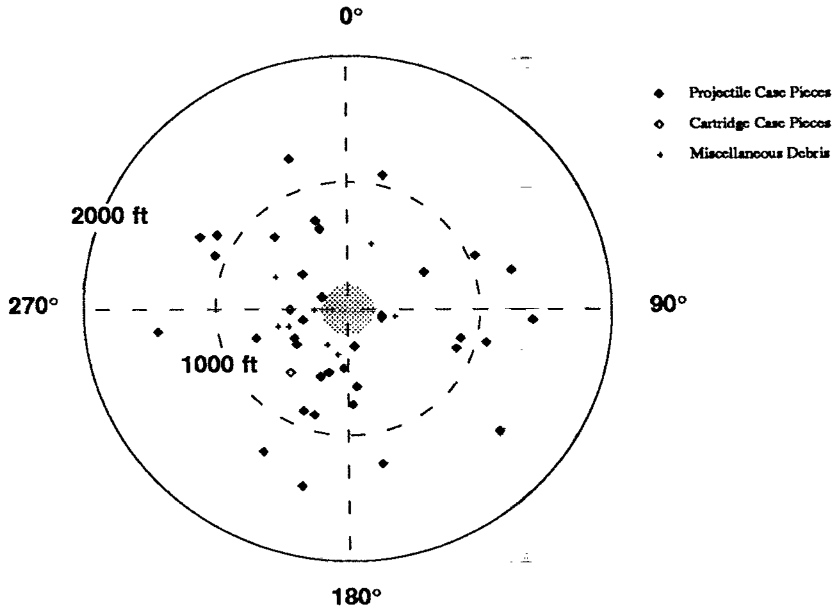


Figure 9. Approximate Distribution of Far-Field Fragments After Third Single Pallet Test

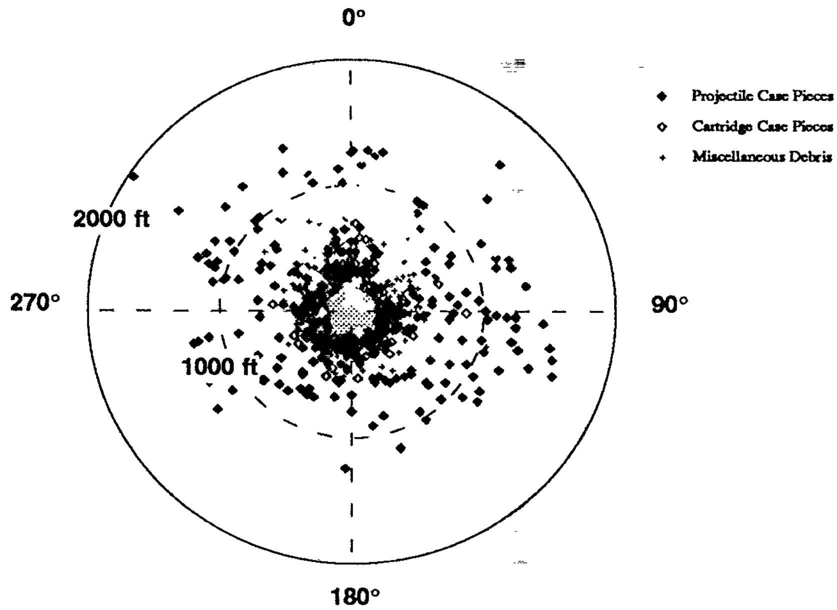


Figure 10. Approximate Distribution of Far-Field Fragments After First 8-Pallet Test

Figure 11. Typical Projectile Case Fragments from Single Pallet Tests

Figure 12. Typical Projectile Case Fragments from First 8-Pallet Test

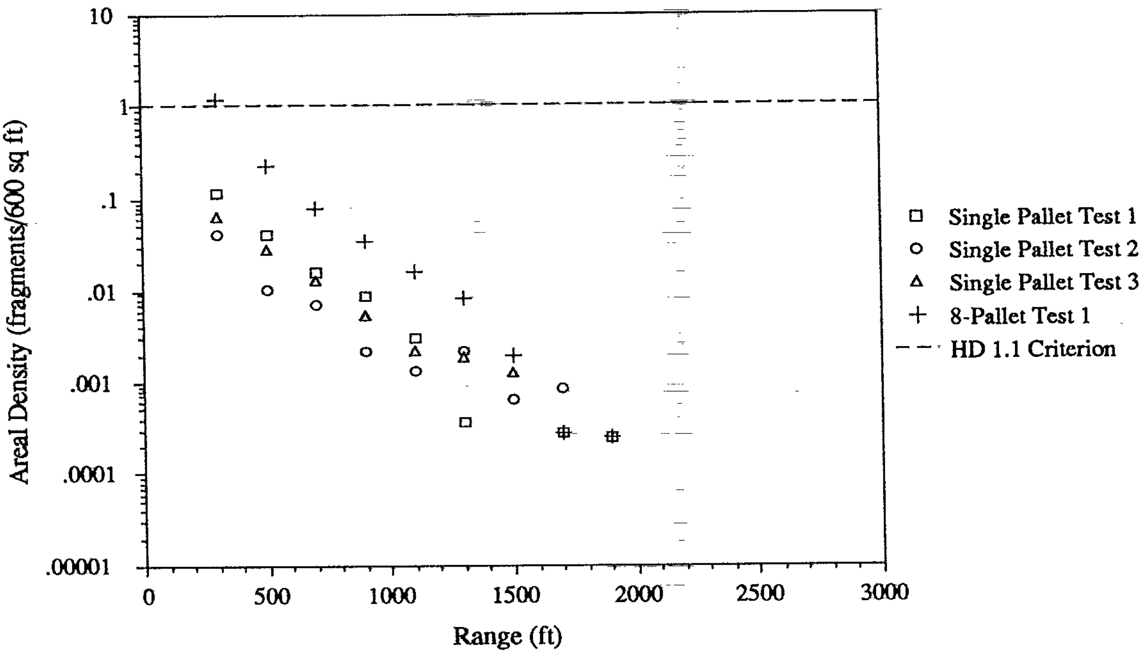


Figure 13. Indicated Fragment Densities Based on Numbers of Fragments Actually Recovered

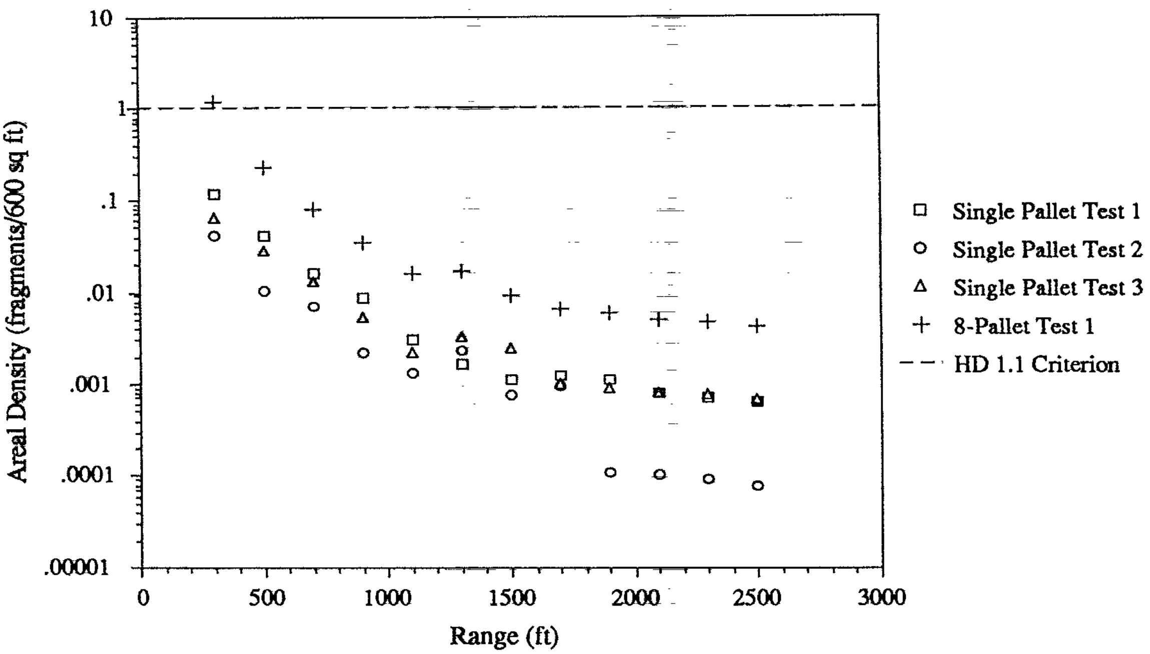


Figure 14. Fragment Densities Obtained Using Adjusted Fragment Counts

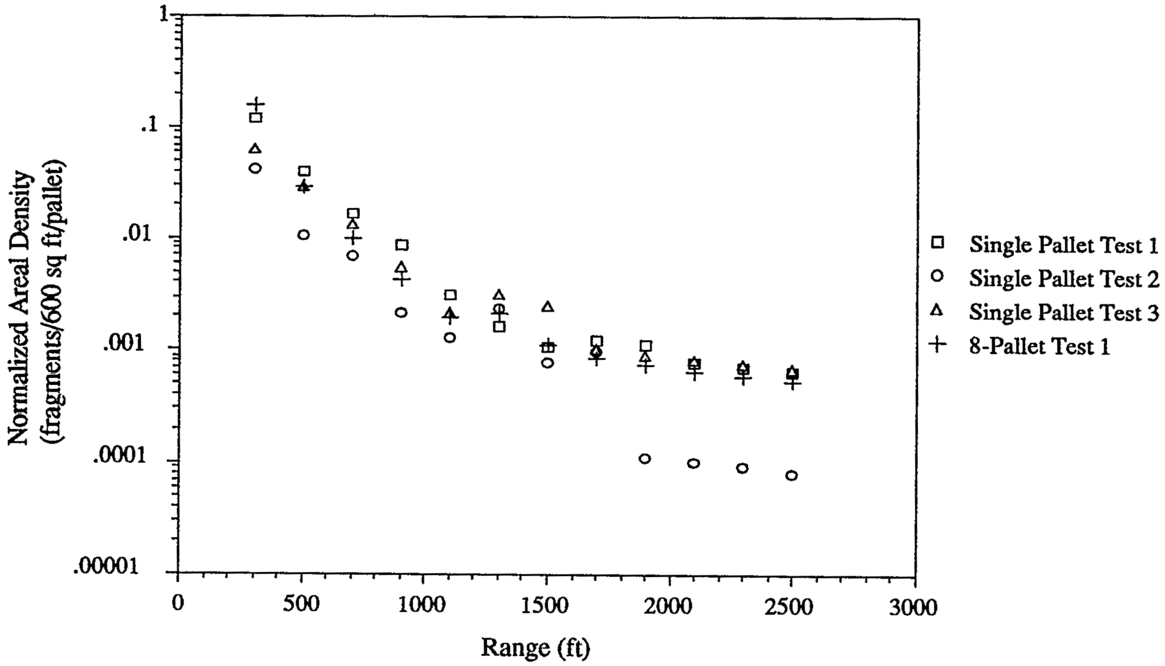


Figure 15. Normalized Fragment Densities

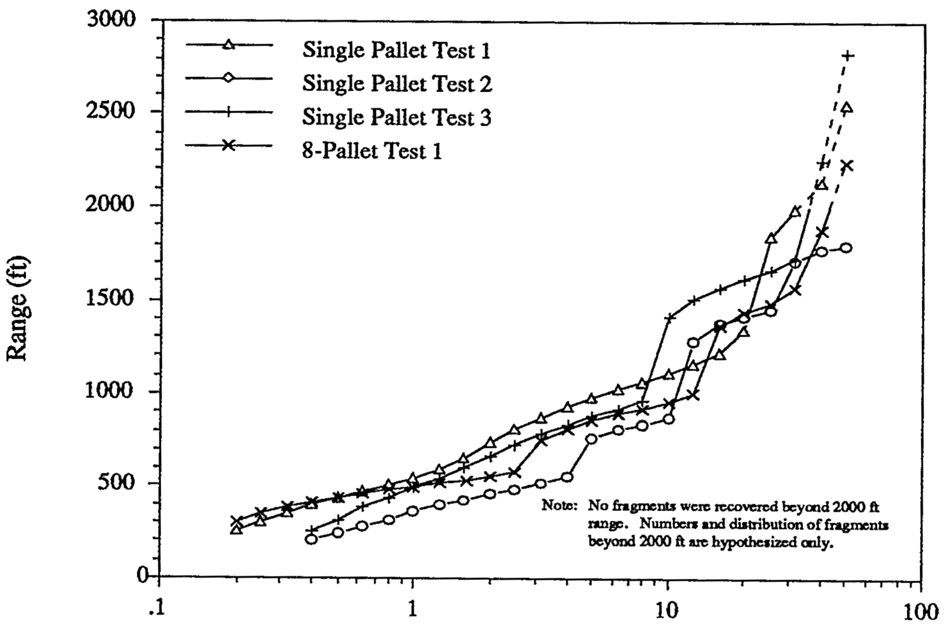


Figure 16. Estimated Ranges to Exceed 1 Lethal Fragment Per 600 sq ft
Based on Scaled Single Pallet and 8-Pallet Test Results

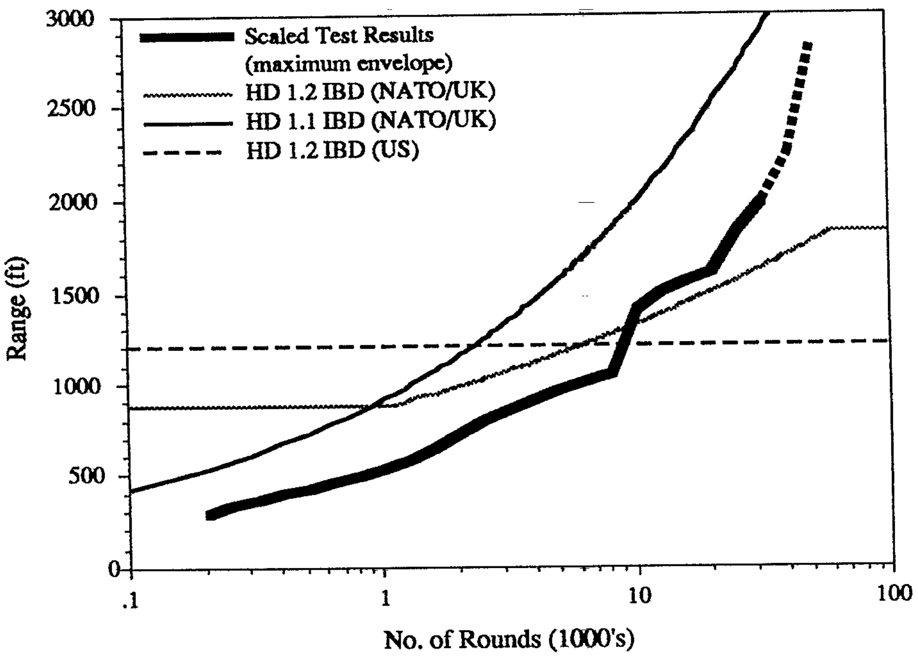


Figure 17. Comparison of Estimated Ranges to Exceed 1 Lethal Fragment per 600 sq ft With Current Quantity-Distance Requirements

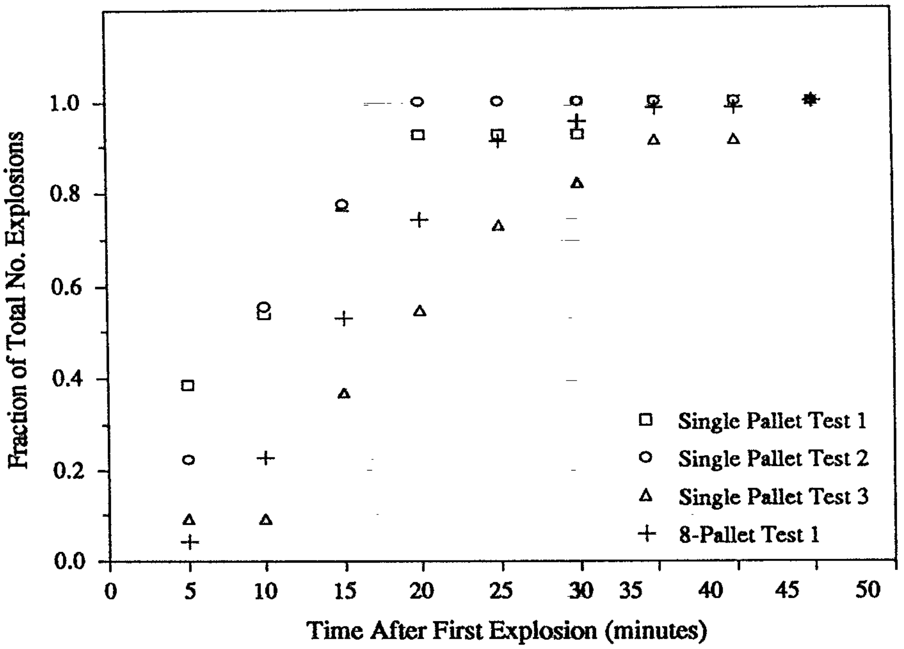


Figure 18. Cumulative Frequency Distributions of Explosions